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Adapting to changes in volcanic behaviour: Formal and informal interactions for enhanced risk management at Tungurahua Volcano, Ecuador

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ABSTRACT

This paper provides an example of how communities can adapt to extreme forms of environmental change and uncertainty over the longer term. We analyse the interactions between scientists, communities and risk managers and examine the interpretation and communication of uncertain scientific information during a long-lived volcanic eruption in Tungurahua, Ecuador. This is complemented with a detailed study of the eruptions of 2006 and 2014, which exemplifies the complexity of interactions during periods of heightened volcanic activity. Our study describes how a 'shadow network' has developed outside of, but in interaction with, the formal risk management institutions in Ecuador, improving decision-making in response to heightened volcanic activity.

The findings suggest that the interactions have facilitated important adaptations in the scientific advisory response during eruptions (near-real-time interpretation of the volcanic hazards), in hazard communication, and in the evacuation processes. Improved communication between stakeholders and the establishment of thresholds for evacuations have created an effective voluntary evacuation system unique to Tungurahua, allowing people to continue to maintain their livelihoods during heightened volcanic activity and associated periods of uncertainty. Understanding how shadow networks act to minimise the negative consequences of volcanic activity provides valuable insights for increasing societal resilience to other types of hazards.

1. Introduction

Volcanic hazards such as pyroclastic density currents (PDC; rapid, hot avalanches of volcanic rocks, ash and gases), lava flows and lahars (volcanic mudflows) can cause total devastation in their immediate path, so managing volcanic risk often requires the temporary displacement of communities around volcanoes. As for many other natural hazards, forecasting volcanic hazards is inherently uncertain, but volcano monitoring institutions also provide valuable advice on preparing for, and mitigating, volcanic risk (Lockwood and Hazlett, 2010). Monitoring has improved and deaths from volcanic eruptions have declined in the last century (Auker et al., 2013), alongside the development of more comprehensive disaster risk management (DRM) systems. Yet data from UNOCHA demonstrates that at least 2 million people were displaced as a consequence of volcanic activity in the last 30 years, even with comparatively few recent large-scale events, in comparison to the long-term eruptive record (Pyle, 2015). As with many other environmental hazards, there are significant negative social and economic impacts of displacement as a result of volcanic activity (Lane et al., 2003; Tobin and Whiteford, 2002; Hicks and Few, 2015; Armijos and Few, 2015; Few et al., 2017); and studies highlight the need for DRM systems to minimise the immediate impacts and at the same time protect people's lives and livelihoods over the long term (Wilson et al., 2012).

Volcanic activity can continue, often intermittently, for weeks, months or even years and so displacements can last for long periods or even result in abandonment of settlements altogether (Plymouth in Montserrat). The enforcement of evacuations varies from setting to

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setting, but most often involves the declaration of high risk or 'forbidden' zones (Mei et al., 2013). In recent years several deaths have occurred within such zones as populations have struggled to adhere to the rules when faced with the stronger imperative of sustaining their livelihoods (including Merapi and Sinabung in Indonesia, and Montserrat in the Caribbean) (Mei et al., 2013; Usamah and Haynes, 2012; Loughlin et al., 2002). A growing body of literature highlights the need to understand the long term implications of volcanic activity for people's livelihoods and wellbeing (e.g. Kelman and Mather, 2008; Hicks and Few, 2015; Thorvaldsdóttir and Sigbjörnsson, 2015; Armijos and Few, 2015) yet little attention has been paid so far to the local DRM systems and how these can evolve to reduce the negative impacts of volcanic activity on the lives and livelihoods of people living in close proximity to volcanoes.

The paper highlights the role of the 'shadow network', essentially a set of informal institutional arrangements and interactions that have developed alongside formal DRM structures in response to activity of Tungurahua volcano, Ecuador. The network has facilitated improvements in monitoring, communication and evacuations, allowing people to maintain their livelihoods during heightened volcanic activity. Shadow networks are defined as being the subset of informal institutions that interact with formal governance systems. The paper examines the interactions between scientists, communities and risk managers in the interpretation and communication of uncertain scientific information and in evacuation processes, as examples of how communities at risk can adapt and respond to apparently extreme forms of environmental change.

The paper first introduces the case study, the theoretical framework and methods used to conduct the data analysis. It then presents a detailed analysis of empirical data relating to hazard monitoring, communications and evacuation processes for two specific time periods of escalations in volcanic activity, 2006 and 2014, and discusses the main insights emerging from the case study. Understanding how shadow networks work to minimise the negative consequences of volcanic activity potentially provides valuable insights for increasing societal resilience to other types of hazards.

2. Repeated shocks: changes in volcanic behaviour since 1999 and the need to adapt

Tungurahua volcano is located on the Eastern Cordillera of the Ecuadorian Andes (long: 78.45W, lat: 1.47S, alt: 5023 masl.) and covers part of the territory of two provinces, Tungurahua and Chimborazo. The volcano is surrounded by several towns at varying elevations (see Fig. 1) and it is estimated that more than 30,000 people live in both rural and urban areas where the volcano poses a threat to life. Areas outside the main influence zone of the volcano, that also experience sporadic ash falls, have a population of more than 200,000 (INEC, 2010; Mothes et al., 2015).

Since 1534 (or the beginning of Spanish colonial times when written records are available), there have been four major historical eruptive episodes of Tungurahua, one every century. These lasted between two and five years, with the exception of current activity, which started in 1999 (Hall et al., 1999). Historical volcanic activity is characterised by relatively small explosive eruptions (Volcanic Explosivity Index 2 and 3) with volcanic hazards including lava flows, volcanic ash fall, and PDC's. Geophysical activity is monitored at Tungurahua by the Geophysical Institute of the National Polytechnic School (IG-EPN), an autonomous agency, funded by the state, responsible for seismic and volcanic monitoring and scientific advice to the national government. In September 1999 IG-EPN established the Observatorio del Volcán Tungurahua (OVT), sited 13 km from the volcano with a direct view of the volcano's NW flank (Fig. 1).

From April 1999, the volcano showed increasing activity, with a sequence of seismic events consistent with the transport of magma to the surface. This began with volcano-tectonic (VT) and long-period (LP) earthquakes, followed by increasing sulphur dioxide (SO_2) emissions, and volcanic tremor signals (seismicity suggesting shallow magma storage) (IG-EPN, 1999). Between 5 and 15 October, a series of small explosions was followed by ground deformation and visible incandescence (magma reaching shallow levels and the surface). On October 15, IG-EPN recommended raising the alert level and national authorities responded by evacuating approximately 26,000 inhabitants from areas around the volcano (Le Pennec et al., 2012; Tobin and Whiteford, 2002). On October 16, local residents were given 30 h to leave voluntarily after which about 50% of the residents were forced to evacuate by the military (Tobin and Whiteford, 2002). Due to a limited availability of shelters people had to move in with family and friends outside the high risk areas, to rent accommodation or live on the streets in nearby cities. In the midst of much confusion, many sold their property and animals for much less than market value (Lane et al., 2003; Tobin and Whiteford, 2002; Armijos and Few, 2015; Few et al., 2017). Volcanic activity then declined, but the lack of an official decision to reoccupy evacuated areas led to confrontations between local residents, the police and the military. National authorities went on to lift the restriction and allow residents back (Vieira, 2003), but the large-scale evacuation, loss of property and livelihoods and social upheaval has had long-lasting effects on the local population and resulted in widespread distrust in authorities and scientists (Lane et al., 2003; Tobin and Whiteford, 2002; Armijos and Few, 2015; Few et al., 2017; Mothes et al., 2015).

From 2000 to 2006 volcanic activity at Tungurahua was characterised by intermittent periods of intense seismic activity followed by small Strombolian eruptions (discrete explosions) and ash falls, with subsequent rainfall-triggered remobilisation of ash as lahars, interspersed with periods of quiescence (Arellano et al., 2008). During these years, intense ash falls and lahars impacted farmers on the slopes of the volcano, destroying crops, killing animals and damaging access roads and other infrastructure (Le Pennec et al., 2012; Sword-Daniels et al., 2011). The biggest challenge for DRM came in May 2006, when increasing seismic activity at the volcano culminated in a sustained explosive eruption on 14 July, which lasted over four hours. It generated the first PDC since the start of volcanic unrest in 1999. On 16 August 2006, a series of Vulcanian explosions (explosive eruptions that can be sustained for seconds to a few minutes), was followed by a stronger sustained explosive eruption, that lasted over 16 h. This eruption produced several PDC, killing 6 people and destroying more than 50 homes on the flanks of the volcano (Mothes et al., 2015; Valencia, 2010). The impact caused by the 2006 eruptions prompted the state and Non-Governmental Organisations (NGOs) to build resettlement homes for those living in high risk areas (Reliefweb, 2006). Despite this, hundreds of families continued to live and/or work on the flanks of the volcano to sustain their livelihoods.

After the August 2006 eruption, the volcano showed intermittent activity, predominantly producing ash fall that impacted agriculture and aviation routes, and PDC which did not extend beyond the uninhabited upper flanks of the volcano. A new phase of energetic and more frequent Vulcanian eruptions occurred between August 2012 and August 2014. Several of these eruptions produced PDC, for instance, in July and October 2013 (Hall et al., 2015) and February 2014, but in general these were less extensive than those in July and August 2006. Between 2010 and the date of writing, the eruptive episodes have become shorter in duration but marked by more intense explosive activity (Hall et al., 2015; whole sequence illustrated in Fig. 5 of, Mothes et al., 2015).

The physical nature of the hazard has changed since 1999, as have the livelihoods and the societal conditions of the population. Settlement patterns, access to services and infrastructure, and livelihood activities in urban and rural areas on the slopes of the volcano, have all been impacted by —and had to change in response to—volcanic hazards in Tungurahua (Few et al., 2017). It is in this changing environment that formal and informal institutions have interacted through a 'shadow

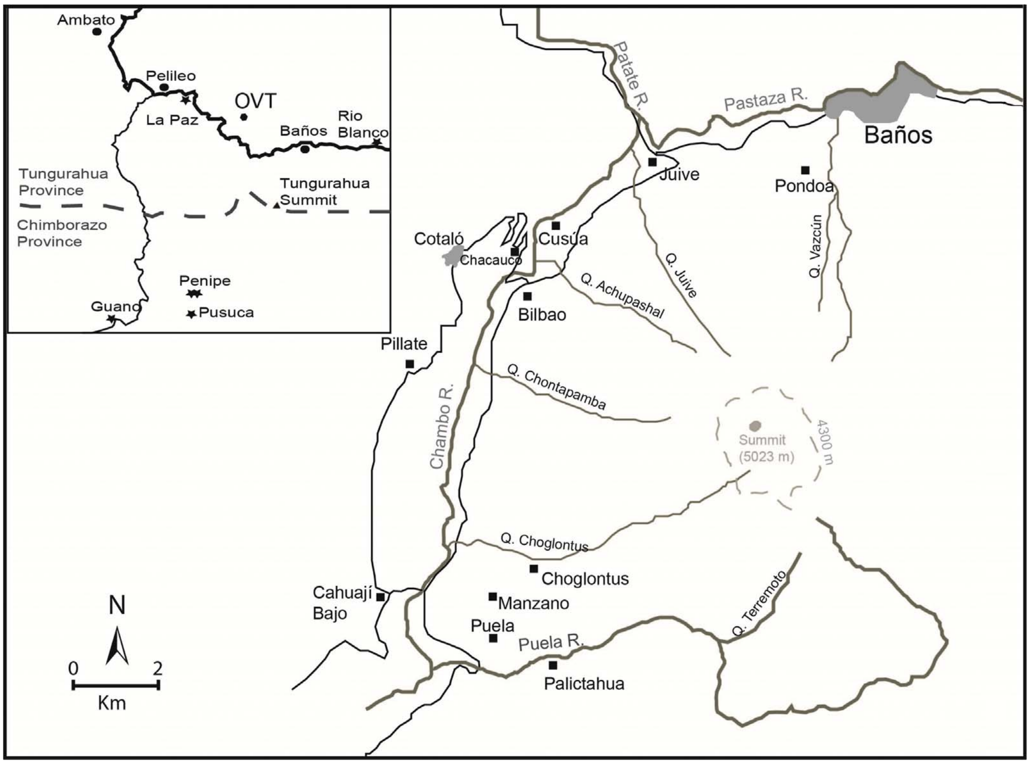

Fig. 1. Map of Tungurahua volcano showing towns, villages resettlement sites and the OVT (Tungurahua volcano Observatory). Map adapted from Few et al. (2017).

network' for DRM, which has played an important role in managing risk.

3. Formal and informal interactions in disaster risk management

Risk management systems undergo changes in line with broader governance trends and shifts, but are also modified during and after disasters and in response to social pressures (Kingdon, 1995), with feedback processes that are non-linear and unpredictable (Ramalingam et al., 2008). Some DRM systems will collapse, while others adapt and re-organize, retaining their basic functions, structure and identity (Adger et al., 2005; DFID, 2011; Berkes et al., 2003; Pelling, 2011; Walker et al., 2002).

Similarly, the hazardous processes themselves can also be dynamic. Volcanic eruptions can persist for weeks, months and even years and can variably impact the communities that surround them. Volcanoes can exhibit a range of behaviour, with one eruptive episode potentially changing the outcome for a later event, along with the likelihood of cumulative impacts (Cashman and Sparks, 2013). In these dynamic environments, formal and informal institutions interact to shape collective action decisions to manage risk (Tierney, 2012; Wilkinson, 2013). These formal institutions comprise legislation and parliamentary procedures for DRM, standard operating procedures and other formal arrangements guiding actions and interactions between stakeholders; while informal institutions include relationships of kinship and customary practices, incorporating different knowledge sources and competencies (Handmer and Dovers, 2007; Newig et al., 2010; Pelling and Holloway, 2006). In a crisis, where the "time to think, consult and gain acceptance for decisions is highly restricted", decision-making processes and actions are often *ad-hoc* and reactive (Boin et al., 2005:11). On the other hand, well-established informal institutions for risk management are more likely to promote adaptation and learning from disaster response (Wenger, 1998). Indeed, high exposure to threats and repeated events over time can create opportunities for experiences that enhance overall system resilience (Moser, 2008).

The interaction between formal and informal institutions also influences how organisations and individuals respond to a particular threat or event. Where these are separate, contradictions and tensions may appear; but where formal and informal institutions complement each other they produce more effective risk management practices (Wilkinson, 2012, 2015).

Shadow networks, defined as the networks or spaces of interaction that develop outside of, but interact with, formal institutions, can help to build these complementarities (Folke et al., 2005; Olsson et al., 2006; Pelling et al., 2008). They often emerge spontaneously in response to complex social and environmental problems (Shaw, 1997; Stacey, 1996). Their role in natural resource management and climate change adaptation has been studied in some depth; actors in shadow networks are found to be more flexible and adaptive, willing to experiment and generate alternative solutions, than formal institutions on their own (Folke et al., 2005; Olsson et al., 2006).

Shadow networks are also characterised by their ability to build innovative linkages between entities that were otherwise not connected (Schmidt-Thome and Peltonen, 2006). A number of studies, for example, highlight the role of social networks that link the state and local communities in supporting capacity building for ecosystem management (Berkes, 2002; Folke et al., 2005; Olsson et al., 2004). Another feature of shadow networks is that they are often triggered by a social or ecological crisis and the recognition of the need for an alternative governance system (Olsson et al., 2004; Olsson et al., 2006). The spontaneous civil society response to the Mexico City earthquake, for example, challenged the legitimacy of a highly centralised authoritarian government, which had failed to respond adequately to the disaster (Dynes et al., 1990; Quarantelli, 1993; Quarantelli, 1994). Olsson et al. (2004) observe that more adaptive co-management of ecosystems usually starts with responses to crises by individual actors that then expand to become a network of actors. Overall, however, evidence of how these shadow networks operate in DRM has received less attention and is less common than in natural resource management. More work is needed to unpack the characteristics and roles of their structures vis-à-vis formal DRM arrangements, particularly their ability to respond to the uncertainty and change inherent in hazardous processes.

A feature of formal-informal interactions in DRM is the role that they play in the co-production of knowledge about risk and risk communication. This is particularly pertinent in the case of volcanoes, as the location of volcano observatories near active volcanoes often bring scientists into close contact with communities (Barclay et al., 2008). Tension between public perception and expert judgement is common in hazard assessment and communication (Jasanoff, 2004; Fischhoff, 1995) and this has generated further interest in the co-production of scientific knowledge and practice (Donovan and Oppenheimer, 2014). Similarly, research on DRM emphasises the wealth of knowledge held by communities on the hazards and risk that they face, the need to blend scientific and indigenous knowledge to assess risk (Kelman et al., 2009; Mercer et al., 2010) and the importance of managing risk at a local level (Lavell, 1994; Lavell et al., 2003). Yet when it comes to formulating actions for local-level DRM, the emphasis on co-production is largely concerned with the interactions between the state and society —how local authorities can work in partnership with communities (UNISDR, 2015)— and less on the role that scientists can play (Scolobig and Pelling, 2016; Barclay et al., 2008).

In this paper we consider the very specific roles of shadow networks in hazard interpretation, monitoring and evacuations processes, resulting from the close interaction between scientists, communities and government officials over 15 years in relation to Tungurahua volcano. These networks have important characteristics linked to their role in helping people to make evacuation decisions and are distinct from other social networks that exist in Tungurahua (Jones et al., 2013).

4. Research methods

This paper examines the evolution and interactions of the geophysical monitoring system, the community-based monitoring of the volcano and the official risk management institutions in Tungurahua since 1999. The analysis is based on a review of secondary literature supplemented by primary data generated through 130 semi-structured interviews conducted in Ecuador between July 2013 and December 2014. These interviews were conducted with 14 national, 9 provincial and 14 local level government officials, 3 scientists, 20 community leaders and 70 residents of the flanks of the volcano, as part of the Strengthening Resilience in Volcanic Areas (STREVA) research project (2012–2018). Individuals were selected using purposive and snowball sampling methods and were interviewed by STREVA project researchers.

This is complemented with a focus on two specific time periods of escalating volcanic activity: in 2006 and 2014. These time periods represent important moments in the volcano's behaviour and in the scientific interpretation of it. They are used to study the social responses, and in particular the role of the shadow system in fostering interactions between communities, scientists and local authorities. For the 2006 and 2014 'crisis' periods, we systematically analyse monitoring data, scientific interpretations of the hazards, communications between stakeholders and evacuation behaviour. This analysis is based on data from IG-EPN observatory records and special reports (IG-EPN, 2014a, 2014b, 2006b, 2006a, 2006c), semi-structured interviews conducted with the stakeholders involved in responding to the crises and secondary literature. We also documented communications between stakeholders to analyse the use of common terms employed to describe volcanic activity in Tungurahua.

5. Adaptations and interactions in the risk management system

This section describes the development of the volcanic risk management system at Tungurahua volcano, with a particular focus on decision-making and interactions between local stakeholders in relation to hazard monitoring, interpretation, communication and evacuations. The system comprises formal DRM organisations and procedures, including the IG-EPN and local emergency operations committees (COE), as well as the ongoing instrumental and presential volcano monitoring carried out by IG-EPN staff based at the OVT. It also includes informal arrangements such as the community-based volunteer group that observe the volcano, known as the *vigía* network (Stone et al., 2014). The shadow network links these groups and practices through a set of specific interactions aimed at managing risk. These include informal channels of communication between scientists and authorities; ad-hoc support from the military and local government to move people in and out of high-risk areas during periods of heightened activity; and the community self-organised evacuations, based on monitoring data and on people's own experience and knowledge of the volcano gained over the years.

5.1. The geophysical monitoring system and interpretations of volcanic activity

IG-EPN scientists based locally at the OVT have been monitoring the volcano continuously since 1999 (Mothes et al., 2015). Seismicity, including individual earthquake types (namely tremor, VT, LP and regional non-volcanic earthquakes), are recorded to the nearest minute and used to assess volcanic activity in near-real-time for rapid decision-making. Since early 2000, the scientists have been using the local radio to provide weekly updates about the volcano, and giving talks in communities (Mothes et al., 2015). At this time, a detection system for lahars was installed on the Northern and Western flanks of the volcano. The Tungurahua seismic activity index (IAS) is a measure of the total seismic energy weighted on different volcanic earthquake types, which was calibrated using as reference the seismicity of the period from October 1999 to December 2005 (Palacios, 2016). It has been calculated on a daily basis since late 2005 and provides the scientists with information about the longer-term trends in volcanic activity.

In 2006, ground deformation, gas emission and acoustic signal (infrasound) measurements started to be recorded continuously, improving significantly the capacity to interpret volcanic behaviour. Following the start of volcanic unrest in 2006, IG-EPN started producing special reports and following a communication protocol through which more than 500 local, regional and national authorities are contacted via fax on a daily basis (Mothes et al., 2015). IG-EPN now also publishes daily reports using data from OVT and shares them with the wider public via email lists, the IG-EPN web page and other social media platforms (Twitter and Facebook). During periods of heightened activity, scientists are in constant communication with the authorities, the local COE, *vigías* and radio stations, through different communication media including telephone, radio and social media. IG-EPN scientists interpret data to be able to "provide rapid and frequent briefings to authorities concerning increases in pre-eruption signals and to help them to make critical decisions" (Mothes et al., 2015:6).

Communication of activity level changes is based on years of experience and the development of thresholds, which have allowed scientists at IG-EPN to understand and describe the volcano's behaviour over time. Thresholds in geophysical monitoring data are recognised as levels associated with previous observations of eruptions, either by formal calibration (IAS) or informal comparison (volcano seismicity, deformation and gas emission). Similarly, thresholds for observed volcanic activity are noted in OVT records for both levels of activity (explosion intensity) and the presence of that activity (PDC).

Interpretation of the volcanic activity at Tungurahua has developed in-line with increasing sophistication of the geophysical monitoring network and detailed observations of the texture and composition of erupted rock and gases. The most intense activity in 2006, for example, was inferred to have arisen from the intrusion of a volatile-rich basaltic andesite into the storage region during seismic unrest (Samaniego et al., 2011; Myers et al., 2014). These volatile-rich pulses continue from 2010 to present, but the more violent activity that occurs without warning is attributed to the interplay between this material and stiff viscous conduit plugs developing in the shallow system (Hall et al., 2015). This violent disruption and failure of the conduit plug has comparatively less warning, sometimes only an hour or so, going from a very quiet state to a full Vulcanian style eruption (Palacios, 2016). Surface exhalations

Table 1
Observations shared across 'vigía' network and interpretations as they appear in the published literature. Superscripts refer to sources of scientific interpretation: 1– (Ruiz et al., 2006); 2– (Hall et al., 2013).

Observations	Associated Surface Activity	Interpretation	Usage (from OVT reports)
'Bramidos' (roaring)	Smaller explosions	Repeated minor failures in shallow conduit (Strombolian jetting)[1]	July 2006 (largely by scientists) August 2006, February 2014
'Cañonazos' (cannon fire)	Larger explosions	'Associated with high energy seismic outbursts' Vulcanian explosion from failure in shallow conduit[2]	July 2006 (largely by scientists; observers = 'detonaciones';) August 2006, February 2014
'Movimiento de suelo' (ground movement)	Felt ground motion	Increasing intensity of seismic activity[1]	July 2006, August 2006
'Vibración de ventanas' (window rattling)	Explosions	Increased intensity of Strombolian jetting [1]	July 2006, August 2006
'Caída de ceniza negra y fina' (fine black ash fall)	Ash fall	Possibly new magmatic activity	February 2014
'Caída de ceniza con tamaño de grano como el del azúcar' (Ashfall with grains like sugar)	Ash fall	Increasing intensity of explosions	February 2014
'Caída de cascajo'	Scoria Fall	Larger Explosions	August 2006, February 2014

throughout the activity have been classified seismically using their event source characteristics into explosions, jetting (roaring) and chugging (harmonic tremor) and have been related to differing modes of degassing within the system (Table 1, Ruiz et al., 2006). Chugging signals were first observed in 2004. Large Vulcanian explosions in 2006 were recognised to have high acoustic amplitudes and were accompanied by powerful audio booms ('*cañonazos*'); behaviour also true of later Vulcanian activity (Hall et al., 2015, 2013; Ruiz et al., 2006). The development of these classifications shows increasing capacity to interpret the volcano's sub-surface source activity from monitoring and surface observations, leading to identification of thresholds that can be used to anticipate changes in volcanic activity.

5.2. Community-based monitoring and communications

In early 2000, after the crisis, residents returned to the high-risk areas on the slopes of the volcano, prompting civil defence authorities (in charge of DRM at that time), scientists and the communities to establish an early warning system that would help protect them. At the same time, scientists were interested in accessing more visual observations from different points around the volcano, and communities wanted improved access to official and scientific information. A *vigía* network was set up in response to these various needs, which currently is made up of 35 community-based volunteers who collect and record physical observations of the volcano and manage sirens at the community level (Mothes et al., 2015, Stone et al., 2014). During periods of low volcanic activity, *vigías* communicate with the OVT daily at 20:00 to report their observations. During periods of heightened volcanic activity, communications between the OVT and the *vigías* increase in relation to the activity of the volcano, occur immediately after observable changes, and flow both ways. Observers seek information from the monitoring network that corroborates their visual observations, as one *vigía* explains:

"That is the advantage for us, we have access to the scientists 24 h a day. I feel a lot safer now, because if there is anything unusual, I just ask for information, and they give it to us" (19 February 2014).

Through formal training and regular communication, *vigías* and scientists have developed a shared vocabulary to describe and communicate styles and intensities of volcanic activity. This vocabulary (see Table 1 and depicted in Fig. 2 and 3), is grounded in the physical phenomena observable by the wider community, but also represents a shared interpretation of what is happening inside the volcano. For example, the association of '*vibración de ventanas'* (rattling of windows) with volcanic explosions is prominent in two-way communications between *vigías* and IG-EPN. It is worth noting that the absence of particular phenomena (notably rattling of windows and ground movements) is considered as noteworthy as their presence. The success of the system has also been made possible by scientists' efforts to reach out to the communities during times of volcanic quiescence through formal interactions in training activities and continuous informal meetings and visits (Mothes et al., 2015, Stone et al., 2014).

The roles of the *vigías* have expanded with time. Today, in addition to their formal role in providing observations of the volcano to scientists at the OVT, they also support IG-EPN in helping to maintain monitoring stations and equipment located in remote areas around the volcano (Stone et al., 2014; Armijos and Few, 2015). *Vigías* can receive information from the observatory before the authorities are able to take action and on various occasions they have supported evacuations. This is not a formal requirement but as one *vigía* explains:

"When things get bad we use the car to evacuate people. It is difficult for people to walk […] so when the Geofísico [OVT] tells us 'you need to be prepared, there might be some changes' we let people know […]. People get ready, they put their animals closer to their homes, far away from the rivers, and in the afternoon we leave" (20th of February 2014).

A critical characteristic of the vigía network is that it performs various functions, although the intensity and levels of communication between scientists, vigías and communities differs from place to place.

5.3. The 'official' risk management system

DRM in Ecuador has undergone substantial changes since 1999 (Mothes et al., 2015; Stone et al., 2014; Tobin and Whiteford, 2002; Armijos and Few, 2015). The events of 1999 and the mis-management of evacuations have had a long lasting impact on the lives and livelihoods of those who returned to their homes and who have continued to reside in areas considered to be at high risk. Improving early warning systems and trust between communities, scientists and local authorities has therefore become a priority.

Between 1999 and 2006, local municipalities and civil defence authorities worked together to conduct training and improve shelter availability and evacuation routes. Resettlement sites were also built from 2007 to 2012 to provide alternative homes to residents who lived in high-risk areas. There are 4 main resettlement areas, Rio Blanco and La Paz, in Tungurahua Province, and Guano and Penipe, in Chimborazo Province, where approximately 750 homes have been provided by the state and NGOs (Armijos and Few, 2015). These houses were originally built with the aim of achieving permanent resettlement but nowadays they are used by its residents in a variety of ways. Some families have moved there permanently, some only spend the nights at the resettlement sites while still returning to their land closer to the volcano during the day. Others have chosen to occupy both houses and live part of the week in each one, also using the resettlement home as an evacuation shelter (Few et al., 2017).

By 2008, the most important changes in formal risk management

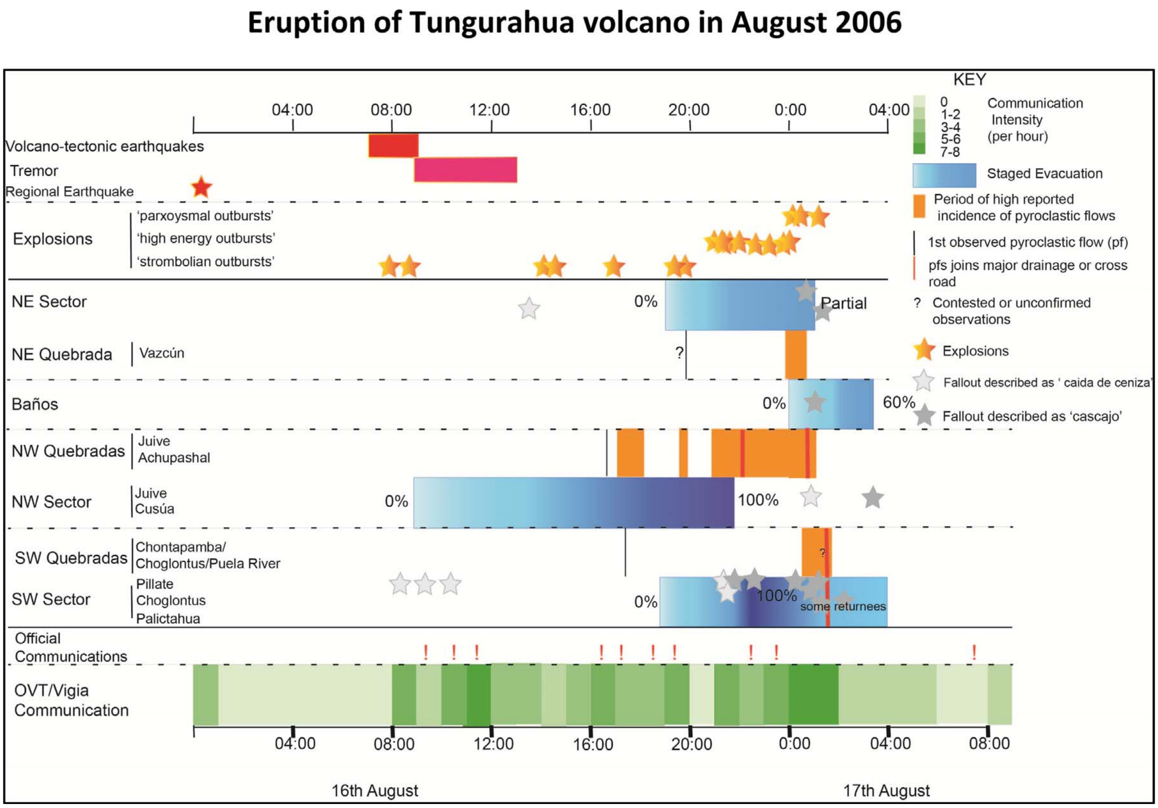

Fig. 2. Timeline of volcanic activity and risk management system and community responses to the eruption of Tungurahua in August 2006. Information shown includes seismic activity (indicating potential eruptive activity), observed volcanic explosions (important in shared vocabulary for volcanic activity), evacuations of population, reports of observed ash fall and pyroclastic flow runout (significant threat to life) in different places shown in Fig. 1, the nature and direction of communications between different elements of the risk management system, and the intensity of communication between the vigías and the volcano observatory (OVT).These data are synthesised from the online records from the OVT (IG-EPN, 2006c), Hall et al. (2013), and interviews conducted in 2014 (Armijos and Few, 2015).

institutions took place via the creation of a new constitution and adoption of a decentralised system of governance in Ecuador. According to Article 390 of the Constitution, disaster risk should be addressed under the principle of subsidiarity, making municipalities directly responsible for managing risk within their territories. If this capacity is surpassed, higher levels of government will provide technical and financial support but should not undermine local responsibility (Constituyente, 2008). In addition, the formal DRM activities of Civil Defence were reassigned to a new Secretary of Risk Management (SNGR), responsible for coordinating all activities related to prevention, response and mitigation of disasters at all levels of government. Local governments are now required to manage emergency funds and allocate resources from their budgets for risk management and coordinate emergency response through the COE, including recommending a change in the alert level to the SNGR (SNGR, 2014).

Since the introduction of these new arrangements in 2008, DRM in relation to Tungurahua volcano has evolved substantially. Local procedures for volcanic emergencies, unique to the Tungurahua context, have been developed, including a local alert scheme designated by colours for levels yellow, orange and red. For example, when volcanic activity is such that an Orange Alert level is issued, officially, evacuation plans should be activated. In practice, people continue with their activities and carry out a partial form of evacuation unique to Tungurahua. This consists of those residents with land on the slopes of the volcano, spending the day working then returning to resettlement sites to sleep at night; a practice made possible by the military providing transport as well as local bus companies transporting people in and out of the communities. Additionally, at this alert level, and when ash fall is intense, the state provides feed for animals through a local distribution programme (Few et al., 2017). This support allows people not only to mobilise in and out of the high risk areas during heightened volcanic activity, but also to help them maintain their livelihood activities in these fertile areas close to the volcano.

At Red Alert level, when an eruption is about to occur or is in progress, and there is observable threatening surface activity, the official local and provincial-level COE are expected to meet to plan and coordinate evacuation and support operations, including the activation of sirens in communities. The police, military and other authorities are expected to carry out the evacuations (SNGR, 2014). Animals are also evacuated from the high-risk areas when high levels of volcanic activity with significant ash fall occurs. For example, in 2006, many animals were evacuated from the slopes of the volcano, preventing people from having to sell their livestock as they had done in 1999. In practice, and despite the extensive preparation and protocols for risk management in the Tungurahua and Chimborazo Provinces, activity levels can and do change faster than the authorities' capacity to react. This was the case in February 2014, when despite the warning sent by the OVT the day before, assistance to evacuate was only provided when surface activity was well underway and some residents had already evacuated.

6. System responses to eruptions in 2006 and 2014

This section examines the use of knowledge produced between communities, scientists and decision-makers in the two crises periods of 2006 and 2014. It highlights a unique role for the shadow network during emergencies and demonstrates differences in collective responses in three different locations: those living close to the volcano on the north-west flanks, those in a high-risk urban area in the town of Baños and those living in rural locations to the south of the volcano (Fig. 1).

6.1. 2006

The eruption of the 14th July 2006 was the first time since 1999 that PDC descended the flanks, posing a significant threat to life. In response to these PDC, an attempted evacuation of communities living at the north and west of the volcano took place. The evacuation was only partially successful (Ramón, 2009; IG-EPN, 2006b) due to lack of decision-making by some local authorities, communication problems and reluctance from the residents to leave their homes. Nonetheless, the observations of surface volcanic activity served to raise awareness among the local communities and test the emergency response.

The main eruption in 2006 started on 16 August and prompted a series of observations, communications and evacuations (see Fig. 2 timeline, with events subdivided by geographical location as shown in Fig. 1). Following an isolated explosion on 14 August 2006, IG-EPN issued a special report to the Governor of Tungurahua, the Mayors of Baños, Pelileo, Penipe, and the civil defence authorities, requesting that they stay alert to volcanic activity. At 08:06 on 16 August, *vigías* started communicating with OVT, with six separate reports of explosions, '*cañonazos', 'bramidos'* (see Table 1 and Fig. 2) and ash falling on the north-west flanks of the volcano. These reports were swiftly followed by official communication from OVT to authorities and to the Agoyán hydroelectric dam, warning them of a new eruption. The municipal authorities in Pelileo and Penipe recommended an evacuation shortly afterwards, and by 11:00 the sirens had been activated. The evacuation of communities on the north-west flanks of the volcano (Juive, Cusúa and Bilbao) was completed in a few hours, with assistance from government authorities and local *vigías* (IG-EPN, 2006c; Ramón, 2009). Later in the evening, a pyroclastic flow destroyed approximately 50 houses in the Juive valley, but no lives were lost. Cooperation between IG-EPN, the *vigía* network and authorities through formal and informal channels had produced an effective evacuation, protecting the lives of those living on the north-west flanks of the volcano.

Response in the town of Baños was slower however. OVT was unable to contact the Mayor of Baños, but was in contact with the COE via the civil defence radio. COE meetings were in session throughout the day, but the alert level was not changed to 'orange' until 18:00, after most people had evacuated from the north-west flank of the volcano. However, people in the Vazcún Valley (a high risk area prone to pyroclastic flows on the north flank of the volcano extending to Baños) did not start evacuating until 19:00, and in contrast to the timely evacuation from rural villages, the response in Baños was more chaotic, possibly due to the electricity supply being cut off and falling of '*cascajo*' (scoria). As the explosive activity increased, people from other neighbourhoods in Baños began to evacuate voluntarily and by 03:00 on 17 August, approximately 60% of the population had moved into shelters (IG-EPN, 2006c:9). Evacuations from villages to the south of the volcano (Manzano, Choglontus and Puela) started after the alert level changed and with the assistance of local *vigías*. By around 23:00 most people had left. However, some decided to stay and others returned to their homes a few hours later and when a large PDC hit the village of Palictahua, 6 residents were killed. Many animals were lost and buildings destroyed (Mothes et al., 2015; Valencia, 2010).

Geographical differences in the timings and effectiveness of evacuations can also be seen in the formal and informal communication processes. The content and number of the *vigía* reports on 16 August reflect the variation in response times (Fig. 2). There were more *vigías* in the evacuated areas west of the volcano and these *vigías* sent more reports to OVT (19 and 18 respectively) than other *vigías*. In comparison, *vigías* to the south of the volcano did not report at all during the paroxysmal phase, some of this biased due to the lack of a repeater to facilitate radio communication. *Vigía* communication evolved throughout the day to acknowledge the greater hazard, with reports increasingly focused on pyroclastic flows and evacuations rather than rain (awareness of lahar threat), ashfall or explosions.

The shared vocabulary allowed rapid communication and common understanding of the intensity of the volcanic activity and its location, such as flows observed at key confluences in the catchment or passing a defined location '*medio cono*' (half way down Tungurahua's flanks). Additionally, Radio bulletins broadcast by the Voz del Santuario (Baños-based radio station) across the entire region were checked by the COE, making them an official source of information for the local population.

In summary, despite the improvements since the 1999 evacuation, notably the voluntary evacuation of most residents on the north west flank of the volcano which saved dozens of lives, in August 2006 some residents still chose to stay in their homes and people in Palictahua lost their lives from a large PDC. The differentiated evacuation process described above may be due to sirens not having been installed everywhere in the Penipe Canton, Chimborazo Province where Palictahua is located, the fact that a PDC had only very recently occurred and was directed to the north-west of the volcano, and that resettlement sites had not been built yet, prevented some people from evacuating. The absence in Palictahua of a *vigía* with a radio that could communicate directly with OVT, might have also played a crucial role in the outcome of the crisis. This highlights the importance of the interaction between the shadow system and the official arrangements elsewhere in the volcano.

By 2006, the presence of the shadow network had resulted in important changes in monitoring the volcano and communication improvements, including in the establishment of a people-centred early warning system. This generated increased trust in scientific information and permitted the DRM system to, at least partially, respond to the challenges posed by increased volcanic activity, despite the legacy of the 1999 crisis.

6.2. 2014

In 2014, the eruption started with low levels of activity on 30 January, prompting a series of observations, communications and evacuations (see Fig. 3, with events arranged by geographical location as shown in Fig. 1). Some seismic precursors to Vulcanian eruptions were recognised by IG-EPN (Hall et al., 2015), and when a significant volcanic tremor was measured on 30 January, OVT alerted the *vigía* network to an increased chance of an eruption. The *vigías* notified local residents and some moved their livestock away from areas potentially threatened by PDC. *Vigías* reported ash fall around the volcano during the day and an explosion occurred at 19:05. At the 20:00 call-in, they reported ash falling and sounds from the volcano. The following day, visibility was hampered by cloudy conditions, and vigía and OVT reports suggested widespread ashfall around the volcano and a single explosion, reported as a 'cañonazo' by vigías located to the west and north-west of the volcano at the 20:00 call-in.

During the morning of 1 February, some of the *vigías* reported continued ashfall, but there were few observations, possibly due to cloudy weather. There was a large seismic swarm between 06:30 and 08:30, and at 12:00 OVT contacted authorities in Baños, the *vigías,* the mayors of communities located to the north, west and south of the volcano, the national risk management authorities and the provincial governors, asking them to be alert in case of a large eruption. At 17:12 and 17:32, two moderately-sized explosions occurred generating ashfall and a small PDC that travelled a few hundred metres down the north-west flanks. At 17:39 a larger explosion produced a PDC that reached much further down the valley bottom, first to the north-west, then south-west, and north of the volcano. People in Cusúa (a village north-west of the volcano) were trapped in between valleys where PDC had been confined. After seeing these hazards, many people in the north-west, west and south of the volcano self-evacuated to safer areas or their resettlement homes, supported by the local vigías. Most residents of Baños did not evacuate.

IG-EPN issued a special report on the eruption at 19:14 (IG-EPN, 2014a) and shortly afterwards the regional and local COEs convened

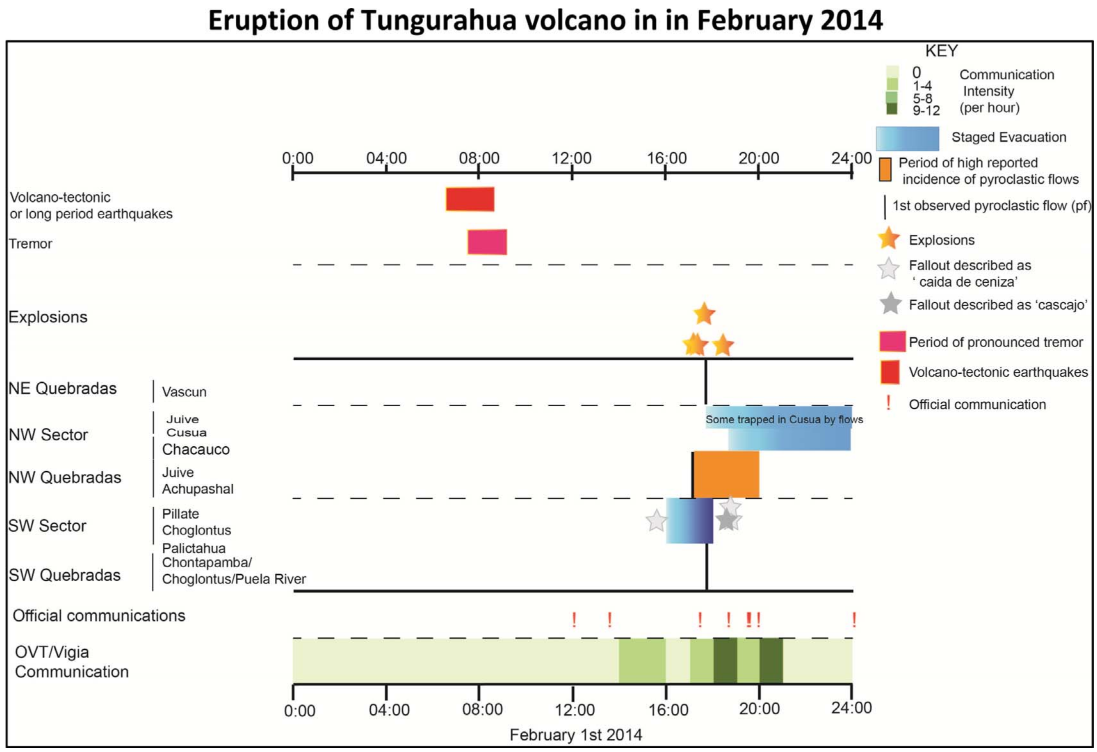

Fig. 3. Timeline of volcanic activity and risk management system and community responses to the eruption of Tungurahua in February 2014. Information shown includes seismic activity (indicating potential eruptive activity), observed volcanic explosions (important in shared vocabulary for volcanic activity), evacuations of population, reports of observed ash fall and pyroclastic flow runout (significant threat to life) in different locations shown in Fig. 1, the nature and direction of communications between different elements of the risk management system, and the intensity of communication between the vigías and the volcano observatory (OVT). Data sources as Fig. 2.

and the SNGR declared an emergency in the provinces of Tungurahua and Chimborazo. Sirens were used in areas to the south-west of the volcano to alert remaining people to evacuate, and the *Voz del Santuario* radio station warned people to avoid the valleys and streams at risk from pyroclastic flows, and to remain calm and wait for official instructions. During the evening, the COE began managing road access preventing people from entering affected areas. On the 2nd of February volcanic activity began to decline and people returned to the area the following day.

In 2014, the *vigías* were able to provide immediate reports of observations of the surface activity, allowing IG-EPN scientists to rapidly assess the progress of the eruption and PDC activity on 1 February, and issue a special report to authorities. Shared communication showed stronger distinctions between different types of ashfall (texture as well as amount) a reflection of the importance of different sub-components of the magmatic system, and improving capacity to interpret the size of explosions in cloudy conditions. The eruption in 2014 showed that despite developments since 2006 in formal and informal communications practices and actions to support evacuations, communities were still vulnerable to rapid-onset volcanic activity. Moreover, because people want to protect their property and animals they are reluctant to evacuate before surface activity is very high.

7. Discussion

Risk governance around Tungurahua volcano has undergone an important transformation since 1999, shaped by a restructuring and decentralisation of the formal DRM system, improved monitoring but also the creation of an informal network that has strong similarities to networks identified in other settings developed for natural resource management (Folke et al., 2005; Olsson et al., 2006). This has helped to facilitate information flows between local actors and promote a more effective response to changes in volcanic risk. As elsewhere, the emergence of this shadow network was driven by a social crisis – the 'disaster' in 1999, which was caused not by the volcanic eruption, but by the poor response at different levels and possible mis-management of evacuations.

In Tungurahua, the shadow network has adapted to deal with the complex socio-ecological problems created by a long-lived volcanic eruption, allowing people to continue farming and maintaining their rural livelihoods in relative safety, while at the same time benefitting from shelter and services in the resettlement sites (Few et al., 2017). The informal exchanges have taken place outside the formal DRM system, but interacting with it in a positive and reinforcing way; made possible by the decentralisation of DRM functions in Ecuador. This has strengthened the capacity of local authorities and permitted decisions about volcanic risk management to be taken at a level where the impacts of volcanic hazards on people and livelihoods can be better understood. The network not only exists in the 'shadows' of the formal system but has strengthened links between different stakeholders: principally, between those communities living in high risk areas close to the volcano, the scientists involved in monitoring the volcano, local risk managers and other government officials and emergency services.

The interactions between communities, scientists and local authorities, have occurred both during periods of quiescence and during heightened activity. They have fostered adaptations in the scientific understanding of longer-term evolution of volcanic activity and the advisory response, and in the speed and effectiveness of communication and enhanced evacuation processes. In 1999 when the eruption began, there had been no volcanic activity for about 80 years, and IG-EPN interpretations of what the volcano was doing were reactive and solely based on changes in geophysical monitoring measurements and observations. There were high levels of uncertainty in anticipating developments in activity. Neither was there a pan-volcano radio system in operation at that time. By 2014, there had been significant 'scientific adaptations', including an improved capability to monitor and to interpret the volcano's behaviour. This resulted in an improved ability to anticipate changes from quiescence to eruption onset, and has led to the use of clear protocols for advice and communication that are linked directly to local risk managers and authorities.

A key element of the shadow network has been its role in generating observations of the volcano in near-real-time, communicated through vocabulary that is understood by scientists and community members. A new shared consensual understanding of thresholds for preparedness action has been generated. Levels of uncertainty in anticipating changes in volcanic activity have reduced considerably since 1999, but the ability to respond to very rapid changes during eruptions still remains a challenge. This will continue to demand rigorous observation, recognition and communication when geophysical changes are rapidly displayed before the onset of Vulcanian explosions.

The 'communication adaptations' have occurred through the development of a shared understanding and vocabulary to refer to volcanic hazards, whereby communities, via the *vigías*, have been able to access and interpret hazards data in conjunction with the scientists. Knowledge about the volcanic hazards - what is happening and what is likely to happen - is generated by combining scientific information with the *vigías*' own observations of the volcano and their years of experience of living through the process. Improved information exchange between these stakeholders has also avoided the common problem of conflicting messages from scientists and authorities, and has improved trust in official messages.

Linked to improvements in communication are the 'adaptations in evacuations' whereby decisions on when to evacuate are taken locally, voluntarily and - in almost all cases - collectively. In 1999, local communities had no prior experience of the volcano being active, or of preparing for an evacuation. The forced evacuation was disruptive and chaotic, generating high levels of mistrust in the scientists and government authorities, but today self-evacuations occur. This has been made possible through the development of shared notions of tolerable risk (Few et al., 2017). The decision to initiate or intensify evacuation activities in 2006 was strongly associated with surface activity (for example, PDC's) passing a defined location (*medio cono*) or with initiation or intensification of ground movement associated with increased explosive energy. These thresholds vary for each geographical and social setting, and they are different for each community (Figs. 2 and 3) (Few et al., 2017). Yet the decision to evacuate is now grounded in these observations and in the knowledge of the community members and improved shelter options - either in the resettlement sites or better-equipped temporary shelters. The rapid onset activity in 2014 proved more challenging, however, with a reduced time interval between the onset of observable activity and the crossing of these tolerable risk thresholds. Nonetheless, the fact that people are willing to evacuate without mandatory evacuation orders means they are better prepared than before. The evacuations are generally well managed and include transport and shelter for animals, which is vital for farmers to be able to return to their activities when volcanic activity declines.

The shadow network has facilitated interactions that take place outside the formal DRM system but, most importantly, also interact with it. The combination of informal and formal observations and interpretations of volcanic behaviour, of communications between local stakeholders and in decision-making processes about when to evacuate, have collectively produced a better outcome than if the same groups had undertaken similar, yet independent actions. The shadow network around Tungurahua volcano has played a key role in improving collective responses to volcanic risk, allowing people to maintain their livelihoods during heightened volcanic activity and minimising the need for forced evacuations, which are highly disruptive. This network has therefore facilitated adaptations in DRM in response to changes in volcanic behaviour; but a step change may now be required to anticipate and respond better to rapid-onset volcanic activity. Finally, the sustainability of this 'shadow' network will depend on how volcanic activity, livelihood activities and governance structures evolve and change over the longer term.

Data

For access to data used to construct fig. 2 and 3 please contact the corresponding author.

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